

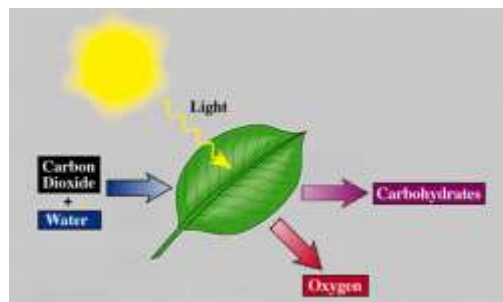
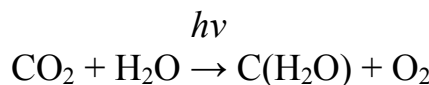
## Photosynthesis: Converting Radiant Energy into Chemical Energy Pigments and Leaves



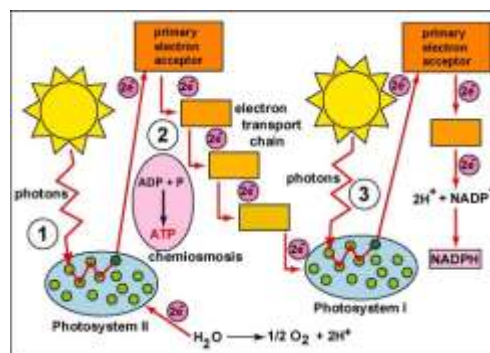
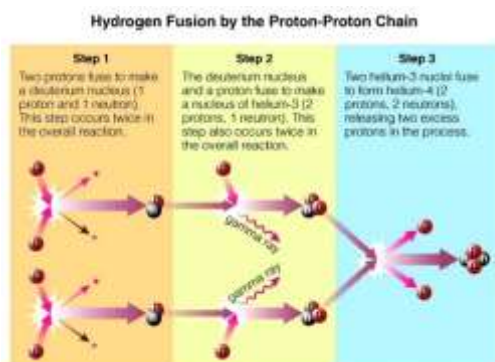
In a speech entitled, *What is Science?*, **Richard Feynman** (1969) said: “As a matter of fact, I can also define science another way: Science is the belief in the ignorance of experts. When someone says, ‘Science teaches such and such,’ he is using the word incorrectly. Science doesn't teach anything; experience teaches it. If they say to you, ‘Science has shown such and such,’ you might ask, ‘How does science show it? How did the scientists find out? How? What? Where?’

*It should not be ‘science has shown’ but ‘this experiment, this effect, has shown.’ And you have as much right as anyone else, upon hearing about the experiments--but be patient and listen to all the evidence--to judge whether a sensible conclusion has been arrived at.”* You can find the whole speech, which includes thinking about photosynthesis [http://www.fotuva.org/feynman/what\\_is\\_science.html](http://www.fotuva.org/feynman/what_is_science.html).

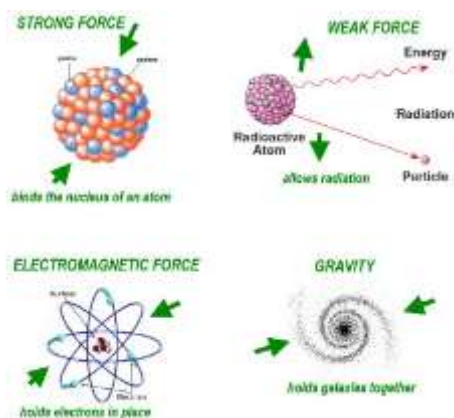
**Photosynthesis** is the **light ( $h\nu$ )-dependent chemical fixation** of gaseous **carbon dioxide** ( $\text{CO}_2$ ) and liquid **water** ( $\text{H}_2\text{O}$ ) into solid **carbohydrate** ( $\text{C}(\text{H}_2\text{O})$ ) with the evolution of **gaseous oxygen** ( $\text{O}_2$ ).



The “*alchemical*” production of sunlight resulted from the rearrangement of **protons** (atomic nuclei). The chemical fixation of carbon dioxide into carbohydrate by photosynthesis results from the sunlight-powered rearrangement of **electrons**.

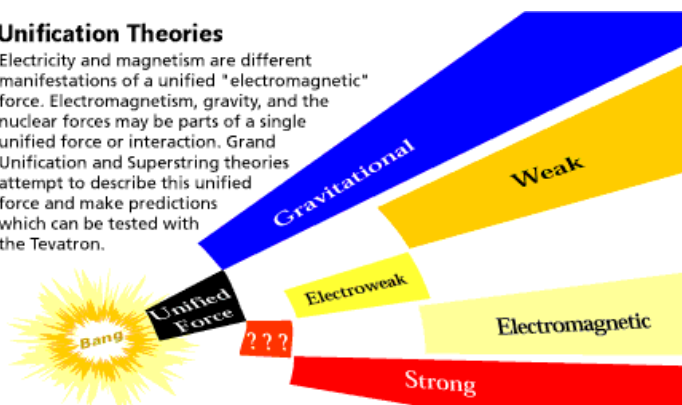


The alchemical production of sunlight involves the **weak and strong forces**. The **weak force** causes the transmutation of a proton into a neutron, a positron and a neutrino. The **strong force** holds protons together in spite of their like charges. The photosynthetic fixation of carbon dioxide into carbohydrate involves the **electromagnetic force**.



#### Unification Theories

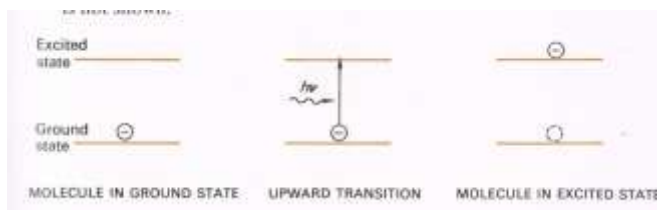
Electricity and magnetism are different manifestations of a unified "electromagnetic" force. Electromagnetism, gravity, and the nuclear forces may be parts of a single unified force or interaction. Grand Unification and Superstring theories attempt to describe this unified force and make predictions which can be tested with the Tevatron.



The fixation of carbon dioxide into carbohydrate involves **the transfer of electrons** from water to carbon dioxide. The **Loss of Electrons** is called **Oxidation** and the **Gain of Electrons** is called **Reduction**. I remember these definitions using

the phrase **LEO** the lion goes **GER**. The negatively-charged electrons ( $e^-$ ) are followed by the positively-charged protons ( $H^+$ ) so that there is a net transfer of  $2H$  from each water molecule to carbon dioxide. This is an oversimplified and **simplistic** way of looking at the chemistry since the transfer takes place in many, many steps. However, this simplistic view leads us to look for a **pigment** that is able to **transfer electrons** in a **light-dependent** manner.

The absorption of light by a molecule such as **chlorophyll**, just like the **absorption** of light by an atom, results in the transfer of an electron from a lower energy **ground state** to a higher energy **excited state**.



It is now a commonplace that in order to use the **radiant energy** ( $E = h\nu = \frac{hc}{\lambda}$ ) inherent in sunlight to fix carbon dioxide and water into carbohydrate, the radiant energy must be **absorbed** by a **pigment**. This is known as the **Grotthuss-Draper Law** or the **First Law of Photochemistry**. **John Draper**

(1841,1872-73), who the keynote speaker at the 1860 meeting of the British Association for the Advancement of Science at Oxford, stated: *“That the ray effective in producing chemical or molecular changes in any special substance is determined*

*by the absorptive property of that substance,” “that it depends on the chemical nature of the ponderable material what rays shall be absorbed,”* and *“the rays*

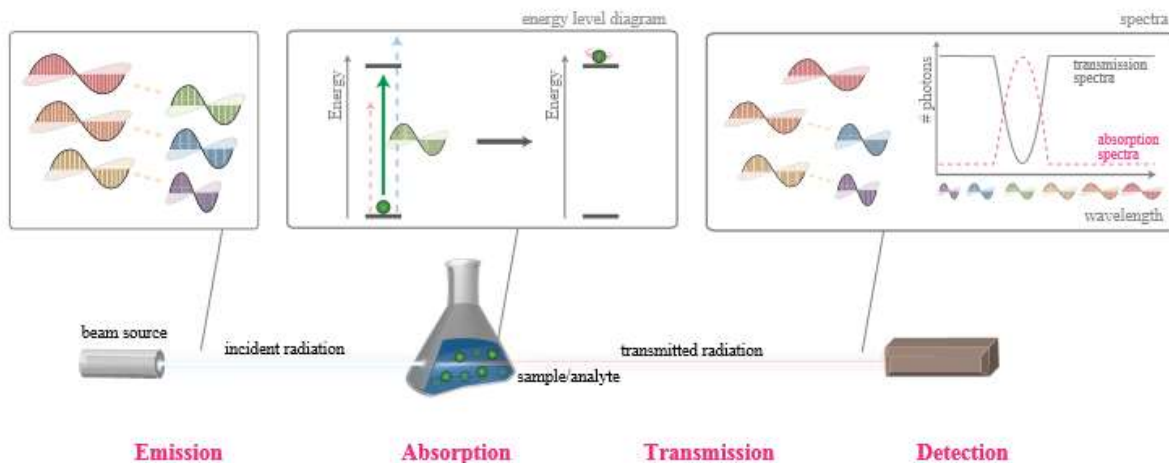


*which are effective in the destruction of any given vegetable color are those which by their union produce a tint complementary to the color destroyed.”*

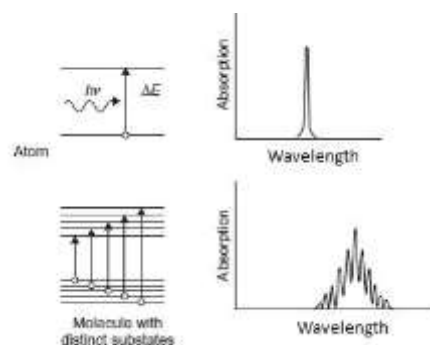
**Theodor von Grotthuss** (1819) performed the original experiments that led to the First Law of Photochemistry. Grotthuss noticed that an alcoholic solution of iron (III) thiocyanate, which is red, became decolorized when it was exposed to light. He also noticed that the rate of decolorization was proportional to the **intensity of the light** and the **duration of the exposure**. After seeing that other colored solutions behaved the same way, Grotthuss concluded that a photochemical reaction could be caused only by the light absorbed by the chemical substance and its **rate was proportional to the light intensity and the exposure time**. Grotthuss also noticed that green light was most effective in decolorizing iron (III) thiocyanate, which is red; blue light was most effective in decolorizing gold chloride which is yellow; and yellow light was most effective in decolorizing a starch iodide solution, which is blue. **John Herschel** (1842) discovered that paper treated with the pigments from flower petals were also decolorized by the **complementary** color. Grotthuss, Herschel and Draper found that **each pigment absorbs the color of light that is complementary to its own color. Its own color is the color that the pigment transmits or reflects**.



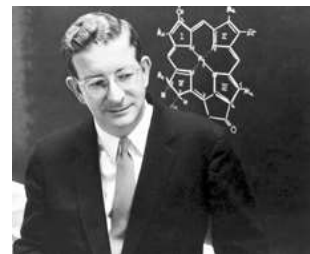
**Absorption** will (probably) occur if the pigment has a **transition energy** value where an **electron** can move from a **ground state** to an **excited state** that corresponds with the radiant energy of the **wavelength** of light.



An **absorption spectrum** of a given pigment is the **probability** that a **photon** with radiant energy ( $E = h\nu = \frac{hc}{\lambda}$ ) will be **absorbed** by that **pigment**. The probability depends primarily on the **chemical structure** of the pigment, although it also depends on the environment (i.e. acidic or basic; oily or aqueous) in which the pigment exists. Since a molecule is composed of many atoms, there are many more **energy states** that correspond to **vibrational states** and **rotational states** between the various **atoms and groups of atoms** that compose the molecule. Consequently, the **absorption spectra of molecules** are broader and more complicated than the **absorption spectra of atoms**. The allowed energy states of atoms, in which the electrons orbit the nucleus, are known as **orbitals** and the allowed energy states of molecules, in which the electrons are shared with one or more atoms, are known as **orbitals**. The allowed states are where the atom or molecule change by **one unit of angular momentum** ( $\hbar = \frac{h}{2\pi}$ , in Joule seconds) during absorption or emission. This is because each photon, no matter what its wavelength, carries exactly one unit of angular momentum ( $\hbar = \frac{h}{2\pi}$ ).

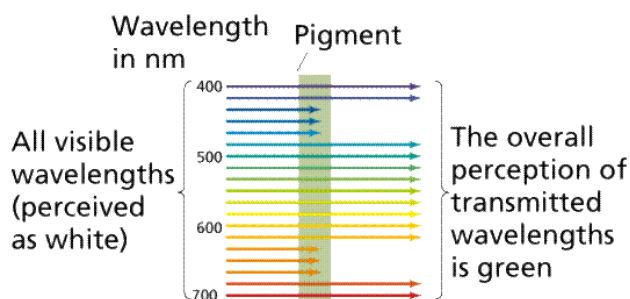


**Robert Woodward** and **Louis Fieser** (who developed **napalm**, an incendiary weapon that is a modern form of **Greek fire**) came up with a **set of rules** that generally predict the **absorption spectrum** of a chemical from the **number of conjugated double bonds that result in the delocalization of electrons**. Each added conjugated double bond shifts the peak of the absorption spectrum from approximately **230 nm by 30 nm towards the red end of the spectrum**. This means the more conjugated double bonds, the more delocalized the electrons are from the nucleus of the atoms and the greater the probability that lower energy photons (i.e. with a long wavelengths) will be absorbed.



**Demonstration:** Extract chlorophyll from *Chara corallina* cells by grinding the cells with a mortar and pestle. Add a little isopropyl alcohol to dissolve the chlorophyll.

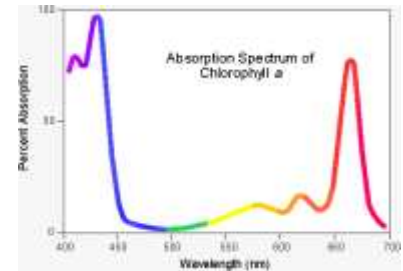
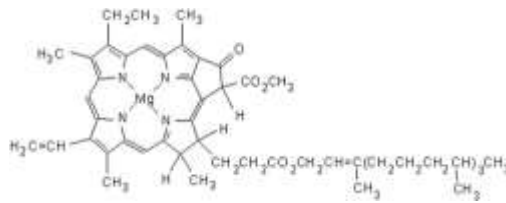
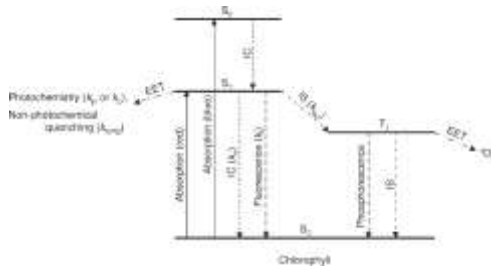
Then pour off the green solution into a little test tube. Use your spectroscope to look at the spectrum of sunlight with and without the



tube containing chlorophyll in front of the slit. Which color(s) do the chlorophyll molecules absorb and which color(s) do the chlorophyll molecules transmit? Is your result consistent with those of Grothuss and Herschel?

The **energy levels** of electrons and the number of **conjugated double bonds** in the pigment can be deduced by looking at the **absorption spectrum**. The absorption spectrum and structure of chlorophyll *a* are given below.

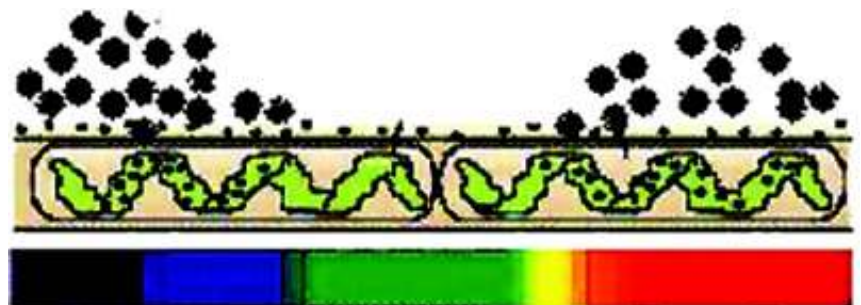




How do we know that chlorophyll *a* is involved in photosynthesis? We compare the **absorption spectrum** of the pigment with the **action spectrum** of photosynthesis. An action spectrum is a test to see which wavelengths of light are most effective in producing the desired response. We could measure the effect of each wavelength of light on **carbon dioxide fixation** using radioactive  $^{14}\text{CO}_2$ , or we could measure the effect of each wavelength of light on **oxygen evolution**. **Theodor Engelmann** determined the effectiveness of each wavelength of light in the 1880s, sixty years before the invention of  $^{14}\text{CO}_2$ , in a very clever way using a microscope.



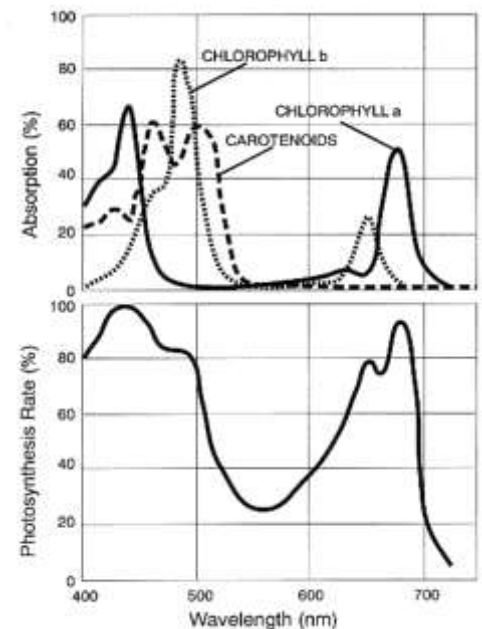
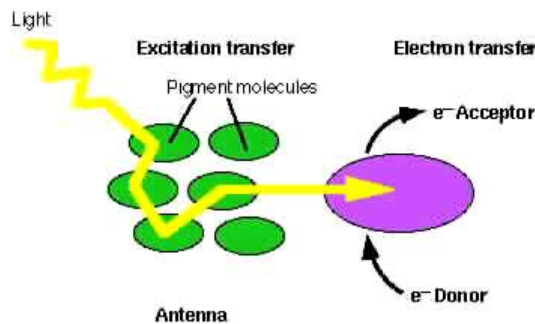
Engelmann projected a spectrum of light on an algal filament on a microscope slide. The most effective wavelengths would result in the greatest production of oxygen. Engelmann then put **oxytactic (oxygen-seeking) bacteria** onto the microscope slide and watched to see where they went. They went to either the blue irradiated region or the red irradiated region, but not to the green region, indicating that photosynthetic oxygen evolution was stimulated most by blue and red light absorbed by chlorophyll and least by green light, the color of chlorophyll.



Thus the **action spectrum for photosynthetic oxygen evolution** determined by Engelmann matched the **absorption spectrum for chlorophyll *a***. This is strong evidence that chlorophyll *a* is the pigment responsible for photosynthesis. If you were wondering, this *is* the same Theodor Engelmann, who was also an amateur cellist, to whom **Johannes Brahms** dedicated Opus 67 for a String Quartet.



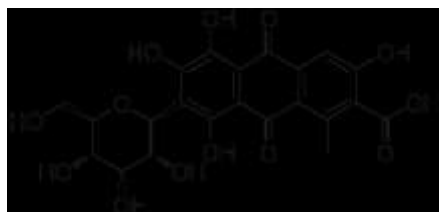
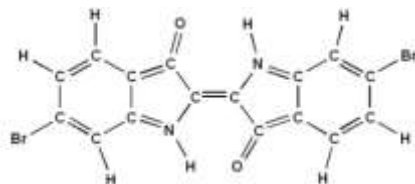
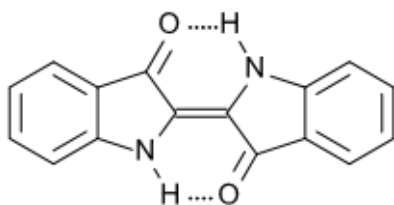
In detail, the action spectrum of photosynthesis does **not** perfectly match the absorption spectrum for chlorophyll *a*. This is because there are **other** pigments involved in photosynthesis that act as **antennae** that capture additional wavelengths of light and transfer the energy to chlorophyll *a*.



A **transparent molecule** is **transparent** because it does **not** absorb visible light. (Later in the semester we will talk about transparent animals). A **pigment** is a molecule that preferentially **absorbs** one or two colors of the spectrum and thus appears as the **complementary color** since the complementary color is **reflected** or **transmitted** to our eyes. Organic pigments used for dyeing textiles and as cosmetics such as **indigo**, **Tyrian purple** and **cochineal** have been part of the human condition for millennia.







Note that these **pigments** look somewhat similar to each other and to **chlorophyll** in terms of having **many conjugated double bonds**. Unlike chlorophyll, the pigments in clothes and lipsticks re-radiate the **absorbed** light as **infrared light (heat)**. However, for a pigment to participate in a light-driven chemical reaction sequence, such as photosynthesis, where the **energy of light** is effectively transformed into the **energy of life**, the pigment must be capable of **transferring an electron** from the excited state of the pigment to an **acceptor** which becomes **reduced** and the pigment must also be capable of **replenishing** the lost electron in the pigment from a **donor**, which then becomes **oxidized**. During photosynthesis, chlorophyll participates in **oxidation-reduction** reactions.

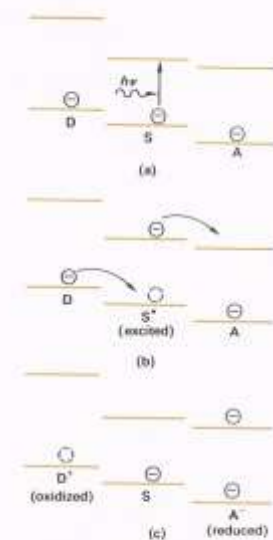
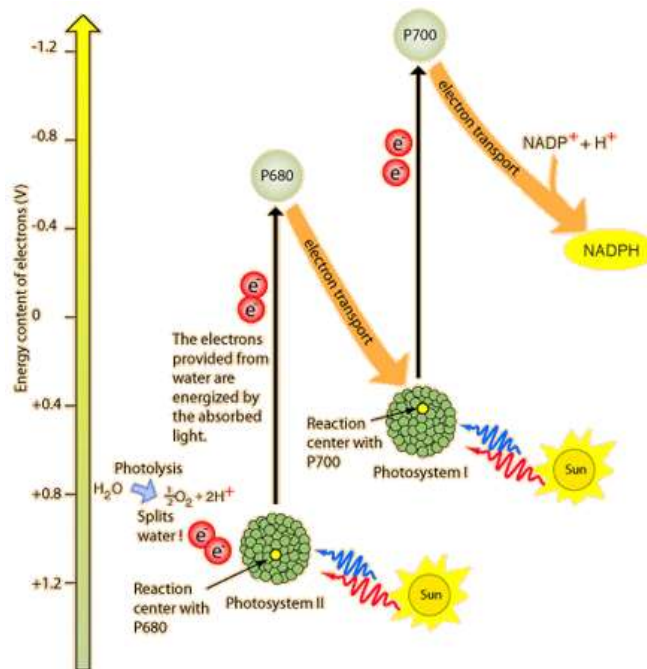


Fig. 2-26. A transition pigment  $S$  can mediate the photochemical transfer of an electron from a donor molecule  $D$  to an acceptor molecule  $A$ .

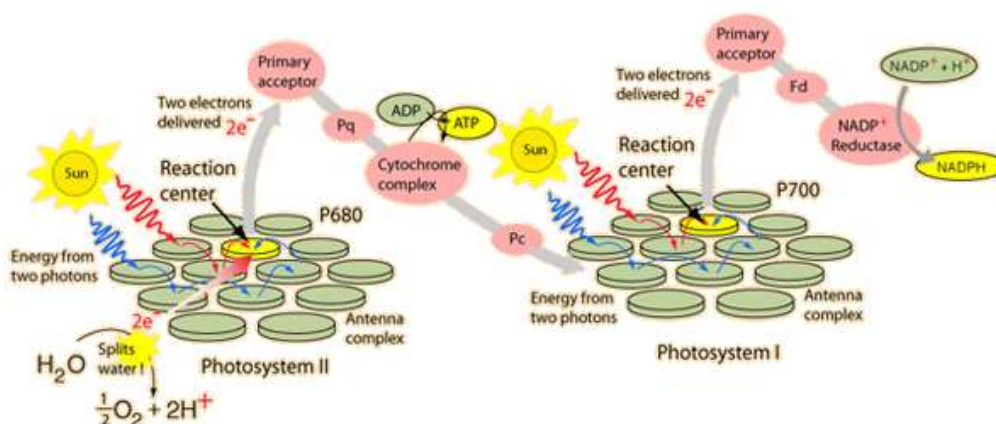
Any molecule that is capable of gaining and losing electrons has what is called a **redox potential**. The redox potential is a measure of the **affinity of the molecule for electrons**. The more negative the redox potential, the more likely the molecule will donate an electron and the more positive the redox potential, the more likely the molecule will accept an electron. When two molecules with different redox potentials are next to each other, the electron is **spontaneously** or **passively** transferred *from* the molecule with the more negative redox potential *to* the molecule with the more positive redox potential and energy that can be harnessed to do the work of life is released in the process.



On the other hand, the transfer of an electron from a molecule with a more positive redox potential to one with a more negative redox potential **requires an input of energy**. Chlorophyll can **actively** transfer an electron from an electron donor with a positive redox potential to an electron acceptor with a more negative redox potential using the **radiant energy** of the **light** that it **absorbs**. The redox potential is given in Volts, but it can be converted into an energy unit in Joules by multiplying the redox potential by a constant known as the elementary charge of an electron ( $ze$ ) and is equal to  $-1.6 \times 10^{-19}$  Coulombs. The difference in the redox energy between the ground state of chlorophyll (1.0 V) and the excited state of chlorophyll (-0.7 V) in photosystem II is  $(-0.7 \text{ V} - 1.0 \text{ V}) * -1.6 \times 10^{-19} \text{ Coulombs} = 2.7 \times 10^{-19} \text{ J}$ . This is equal to the minimum energy of a photon needed to excite an electron in chlorophyll from the ground to the excited state. Given that  $E = \frac{hc}{\lambda}$ ,

what is the minimum wavelength of a photon necessary to raise an electron in chlorophyll from the ground to the excited state? Does 680 nm light have enough energy?

In the light reactions of photosynthesis, there are **two steps**; both involve chlorophyll acting as an **electron pump** that transfers an electron to an acceptor with a more negative redox potential. The two steps are known as **photosystem I** and **photosystem II**.



Each photon absorbed by photosystem I results in the transfer of an electron to  $NADP^+ + H^+$  which eventually becomes reduced to **NADPH**. **Two** molecules of NADPH can provide two hydrogen atoms to reduce **one** molecule of carbon dioxide ( $CO_2$ ) to carbohydrate ( $C(H_2O)$ ). It takes two electrons and thus two photons absorbed by photosystem I to reduce  $NADP^+ + H^+$  to make one **NADPH**. Thus it takes four electrons and **four photons** absorbed by photosystem I to produce two molecules of NADPH. In order to replenish the four electrons from the chlorophyll in photosystem I so that the process can repeat, the chlorophyll in photosystem II must absorb **four photons** and pass them on indirectly through an electron transfer chain to photosystem I. Thus it takes **eight photons** to make **two NADPHs** that are capable of reducing one molecule of carbon dioxide ( $CO_2$ ) to the level of carbohydrate ( $C(H_2O)$ ). The four electrons from the chlorophyll in

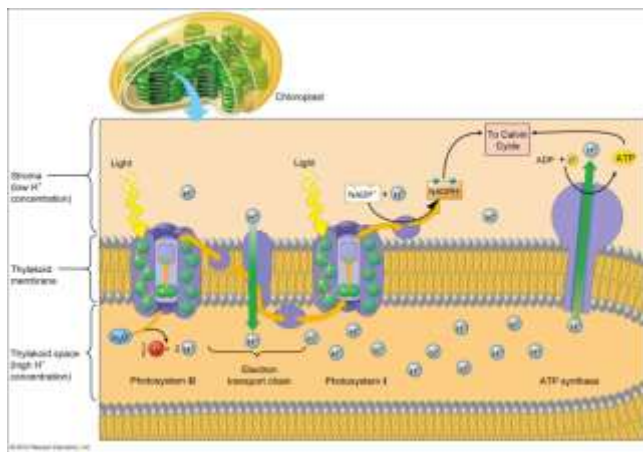
photosystem II are replenished from water. When two water molecules are stripped of four electrons, an oxygen molecule (O<sub>2</sub>) is evolved and four protons are added to the lumen.

The energy ( $E$ ) of a photon of a given wavelength ( $\lambda$ ) is given by the following equation:

$$E = \frac{hc}{\lambda}$$

where  $c$  is the speed of light ( $c = 2.99 \times 10^8$  m/s) and  $h$  is Planck's constant ( $h = 6.626 \times 10^{-34}$  J s). How much energy is in a photon of  $680 \times 10^{-9}$  m light? How much energy is in the eight photons needed to reduce one carbon dioxide to carbohydrate? How much energy is in 48 photons needed to reduce six carbon dioxide molecules to make a six-carbon sugar like glucose? How much energy is in 96 photons needed to reduce twelve carbon dioxide molecules to make a 12-carbon sugar like sucrose?

The light reactions described above take place on the **thylakoid membranes** in the **chloroplast**. The hydrophobic thylakoid membranes composed in part of a lipid bilayer separate two aqueous compartments known as the stroma and the lumen. As the electrons are passed along the **electron transport chain** from photosystem II to photosystem I, they simultaneously transfer protons (H<sup>+</sup>) from the **stroma** to the **lumen**. The buildup of protons in the lumen, including those that are produced by the splitting of water and the depletion of protons in the stroma result in the

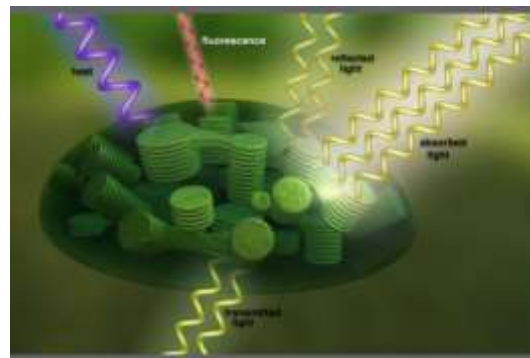


**separation of charge** that is used by a protein known as the coupling factor or **ATP synthase** as an energy source to synthesize **ATP** from ADP and Pi.

As you can see, the light-dependent **separation of charge**, whether the charges stem from electrons or from protons, provides **electrochemical energy** just like a **battery** that can be used to do the **work of life**. No work can be done without an energy input and the energy necessary for the work of life can come from various energy sources (electrical, chemical, gravitational, and radiant), all ultimately derived from the sun's gravitational and nuclear energy (and the initial big bang energy that gave rise to the hydrogen in the sun). This is **the First Law of Thermodynamics**—energy cannot be created or destroyed, but it can be interconverted. The electrochemical energy from the **charge separation of electrons** is used to **synthesize NADPH** and the electrochemical energy from the **charge separation of protons** is used to **synthesize ATP**. In the next lecture, I will tell you how the NADPH and ATP are used in **light-independent reactions** to fix carbon dioxide ( $\text{CO}_2$ ) to carbohydrate ( $\text{C}(\text{H}_2\text{O})$ ).

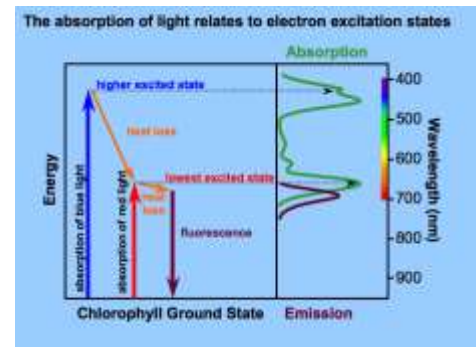


If the plant does **not** have the ability use the NADPH and ATP for fixing carbon in the light-independent reactions, the radiant energy absorbed by chlorophyll could be used to form **damaging free radicals**. Plants have a number of dissipation mechanisms to rid the plant of energy absorbed by the antenna complexes that is in excess of that used to drive the photochemical process of photosynthesis. One mechanism to reduce the production of free radicals is to re-emit the radiant energy as light in a process known as **fluorescence**.

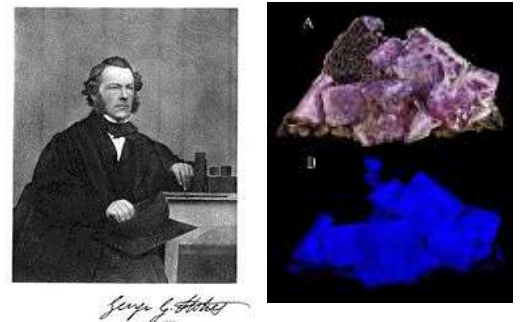




Some of the absorbed energy causes the chlorophyll molecule, which looks as flexible as chicken wire, to bend or vibrate a little. Thus some of the absorbed energy is transformed into kinetic energy and eventually emitted as heat (infrared wavelengths). Since some of the energy of the absorbed light is transformed into kinetic energy, the radiant energy of the light emitted as fluorescence must be less than the radiant energy of the light absorbed. Consequently, the wavelength of the light emitted as fluorescence is longer than the wavelength of the absorbed light.

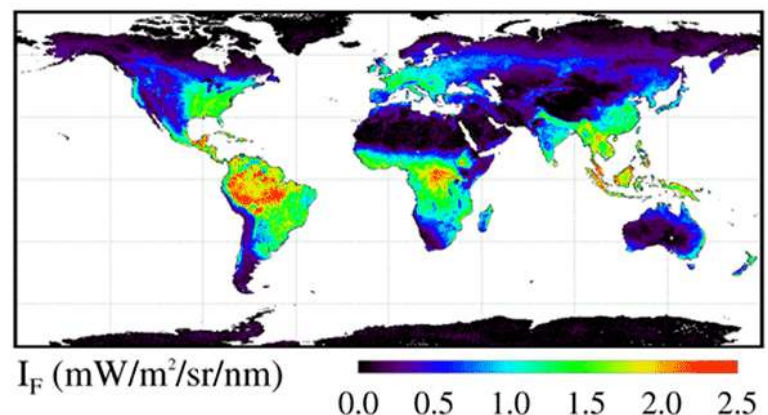


This is known as a **Stokes shift**, named after **George Stokes**, who coined the word fluorescence, named after the mineral **fluorspar** (calcium fluoride), which emitted longer wavelength blue light after it absorbed shorter wavelength invisible ultraviolet light. See the beautiful fluorescence of fluorspar in the **Timothy N. Heasley Museum** in Snee Hall (Cornell).

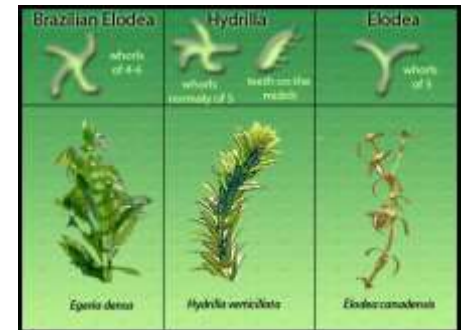


The red fluorescent light emitted by chlorophyll can be monitored by satellite. This **remote sensing** gives an estimate of the global distribution of photosynthesis.

GOME-2, December 2009



**Demonstration:** Using a **fluorescence microscope**, observe the fluorescence of the chlorophyll in chloroplasts of *Elodea* (a relative of *Hydrilla*). What happens to the fluorescence after exposure to blue light?



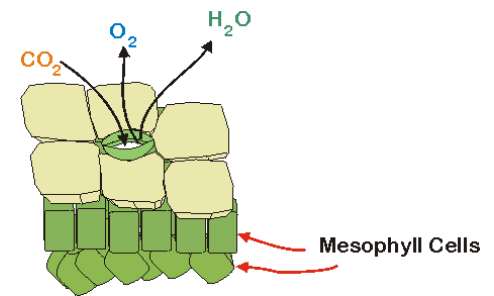
In general, the **leaf** is the **organ** of plants that specializes in photosynthesis. In fact, the word **chlorophyll** comes from the Greek *kloros* and *phyllon* for **green leaf**. Leaves are green because the chlorophyll *a* in them reflects and transmits the wavelengths of light that it does not absorb. Leaves are **not** the only photosynthetic organ. Some epiphytic orchids growing in low light conditions have **green photosynthetic roots**, cacti growing in dry deserts have no leaves, but do have **green photosynthetic stems**, some fruits and seeds, including **Mendel's culinary green peas**, and some flower parts, including the sepals of Cox's Orange and Pippin apples, are also photosynthetic.



The **primary function** of a leaf is to **capture sunlight** and transform the radiant energy into chemical energy with as little as possible of the incident energy transformed into heat. Thus the structure of the leaf **optimizes** photosynthesis under **various constraints**. Remember the tradeoffs of aperture size in the *camera obscura* and Samuel Wilberforce's discussion of selecting for one thing at the expense of another? (Wilberforce Falls on the Hood River in Canada is named after his father, William Wilberforce).



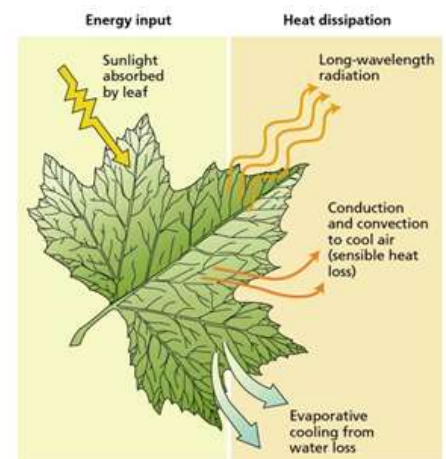
The **carbon dioxide** used for photosynthesis enters the leaf through valves in the leaf called **stomata**. When the valves are open, **carbon dioxide** can enter the leaf and can be converted into carbohydrate; however, at the same time, **water** that enters the leaf by way of the stem and the roots will be lost. If too much water is lost, the leaves will **wilt**, and photosynthesis as well as many other functions necessary for life will shut down.



**Demonstration:** Using a **bright field** or **differential interference contrast microscope**, observe the stomates of *Rhoeo spathacea*.



The bigger the leaf, the more sun it will capture but bigger is not always better since the bigger the leaf the more the leaf will be heated up by the sunlight. Too much heat will result in cooking the proteins in the leaf. Plants use the evaporation of water from the leaf to keep the leaf cool just like we use the evaporation of sweat to cool us. Evaporation and sweating cools the surface because it takes **heat energy to convert a liquid into a gas and the heat energy leaves with the gas**. The amount of carbon dioxide fixed by a leaf and the amount water lost by a leaf must be **balanced**.



Some plants optimize photosynthesis by tracking the position of the sun so that the leaves face the sun throughout the day. Lupin (*Lupinus pilosis*), malva and sunflower (*Helianthus annuus*) are examples of plants that perform **solar tracking** or **heliotropism**.

<http://plantsinmotion.bio.indiana.edu/plantmotion/movements/tropism/solartrack/solartrack.html>



Some species are only heliotropic when they are **well watered**. In times of drought, the leaves close up to minimize the leaf area that captures the sun and results in leaf heating and/or water loss. *Eremalche rotundifolium* pictured on the



left is tracking the sun. Water-stressed *Lupinus arizonicus* pictured on the right has minimized its solar exposure until its water status improves.



Let's look at a leaf that is growing where there is **plenty of sunlight** and **plenty of water**. This is the leaf of the water lily *Victoria regia* that lives in the still waters of the great rivers of the South America that flow into the Atlantic Ocean. In still waters there is a stunning way to collect light for photosynthesis and no plant does this in a more spectacular way than the *Victoria regia*. ***This is a leaf's leaf***. The six foot in diameter leaves float on the still water, supported from the bottom with **girder-like ribs** and **air spaces**.



**Robert Schomburgk** discovered this water lily in British Guiana (Guyana) which was ‘discovered’ by Walter Raleigh in his shipboard (as opposed to alchemical), search for Eldorado—gold. Robert Schomburgk sent a leaf of the water lily along with a description and two drawings back to England. In 1837, **John Lindley** privately published twenty-five copies of a pamphlet on the





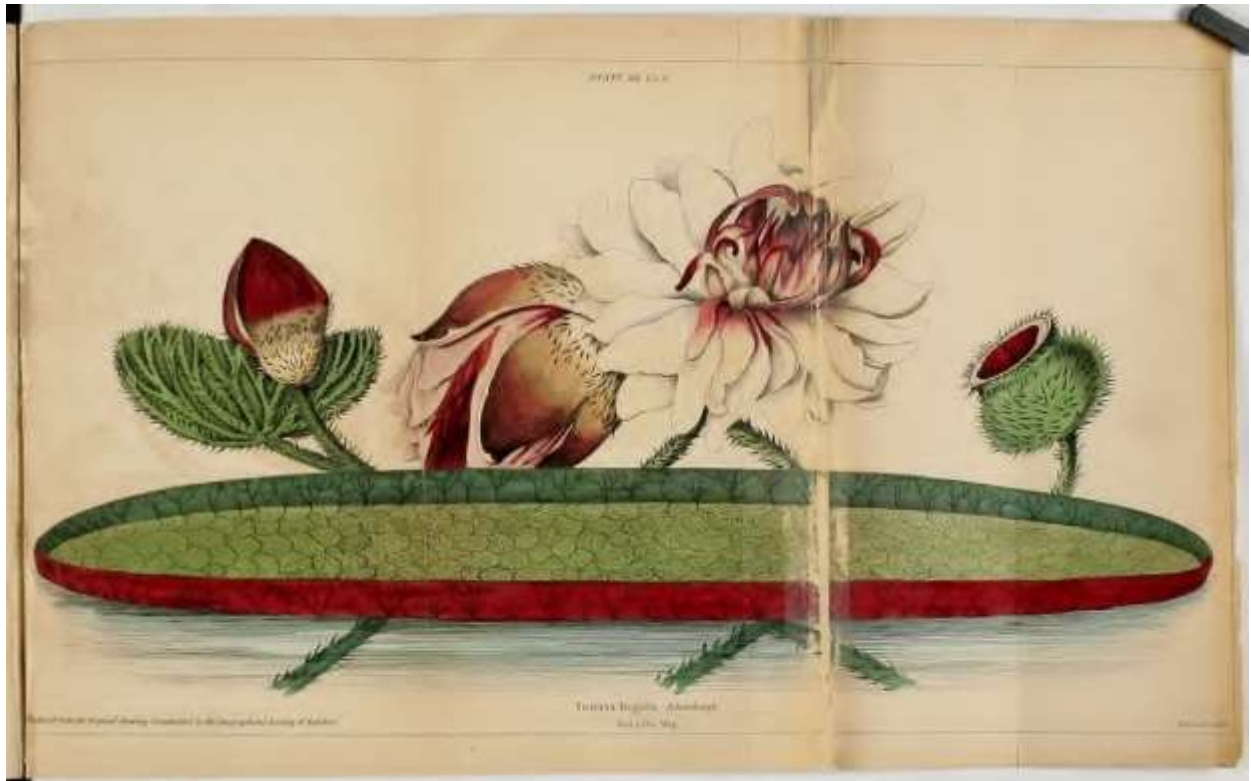
plant he named *Victoria regia*, which included Schomburgk's description of the plant. A month later, John Edward Gray (1837) published Schomburgk's description of the plant and a drawing in the form of an engraving in the more-widely read Magazine of Zoology and Botany. According to

Schomburgk, *"Some object on the southern extremity of this basin attracted my attention. It was impossible to form any idea what it could be, and, animating the crew to increase the rate of their paddling, shortly afterwards we were opposite the object which had raised my curiosity. A vegetable wonder!*

*all calamities were forgotten, I felt as botanist, and felt myself rewarded. A gigantic leaf, from 5 to 6 feet in diameter; salver-shaped, with a broad rim of light green above, and a vivid crimson below, resting upon the water. Quite in character with the wonderful leaf was the luxuriant flower, consisting of many hundred petals, passing in alternate tints from pure white to rose and pink. The smooth water was covered with them, and I rowed from one to the other, and observed always something new to admire. The leaf on its surface is of a bright green, in form almost orbiculate, with this exception, opposite its axis, where it is slightly bent up. Its diameter measured from 5 to 6 feet; around the whole margin extended a rim about 3 to 5 inches high, on the inside light green, like the surface of the leaf, on the outside, like the leaf's lower part, of a bright crimson. **The ribs are very prominent, almost an inch high, radiate from a common centre, and consist of eight principal ones, with a great many others branching off" from them. These are crossed again by a raised membrane, or bands at right angles, which gives the whole the appearance of a spider's web, and are beset with prickles; the veins contain air cells like the petiole and flower stem. The divisions of the ribs and bands are visible on the upper surface of the leaf....When it [the flower] first***



*opens, it is white, with pink in the middle, which spreads over the whole flower, the more it advances in age, and it is generally found the next day of pink- colour."*



In August 1846, fresh seeds of the Victoria water lily were collected in Bolivia by Thomas Bridges and brought to the **Royal Botanic Garden at Kew**. By October, two plants were thriving but by December 12<sup>th</sup> they died.



Other batches of seeds arrived at Kew beginning on February 18, 1849. By March 23, six seeds had germinated and by the end of the summer, fifty plants were thriving. Half of the plants were distributed to cultivators of rare plants, including **Joseph Paxton**, who got a plant on August 3<sup>rd</sup>.



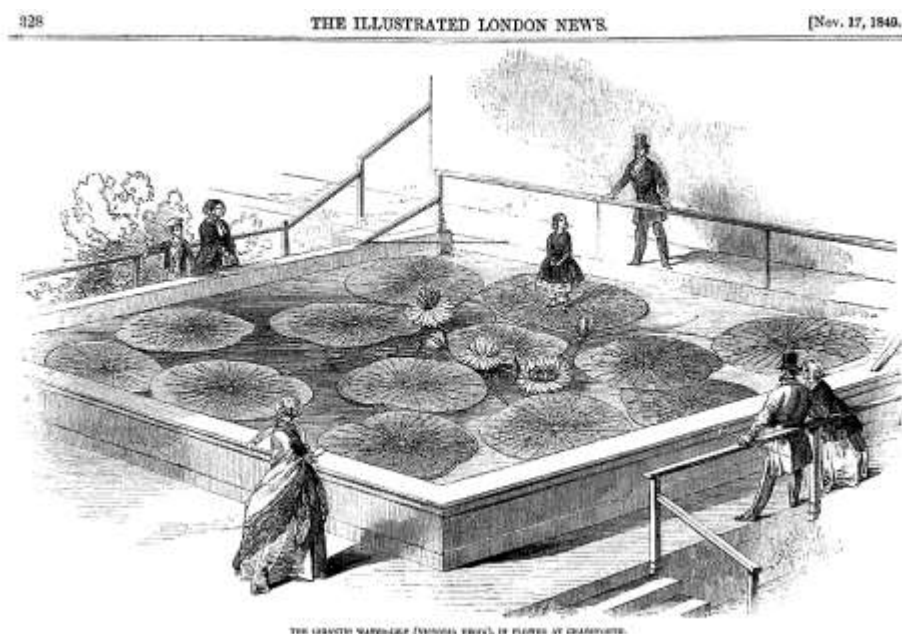
**Joseph Paxton**, the head gardener for the **Duke of Devonshire**, was the first person to successfully nurture *Victoria regia* into bloom in England. The first flower fully opened on **November 9, 1849** in the great glass house he built especially for the water lily in the gardens of **Chatsworth House**.



On November 13, 1849, Joseph Paxton went to **Windsor Palace** to present one of the first blossoms and a leaf to **Queen Victoria**, to whom the genus was dedicated. As reported in the Gardiner's Chronicle in 1850, "*Some of the more vigorous leaves are, at particular stages of their growth, recorded to have*

*increased in diameter at the remarkable rate of sixteen or eighteen inches within twenty-four hours.... The largest flower produced at Chatsworth, of which we have any record, was **thirteen inches in diameter**.... One curious fact connected with the Victoria Water Lily is **the extreme buoyancy of its large succulent foliage, occasioned by the presence of large air-cells in the thick ribs which cover like network the under surface, much aided no doubt by its large surface, and the deep pit-like recesses formed between the interlacing veins. A child seven or eight years of age is said to have been supported by a leaf of the Chatsworth plant. The weight was, however, in this instance, distributed by means of a piece of board laid on the leaf, and on which the child stood.**"*

According to an article published in 1885 by the Wisconsin State Horticultural Society (15: 143-146), "*The event brought together a distinguished concourse of visitors of the nobility and literati. A novel event was the appearance, on the occasion, of little Miss Annie Paxton, who, dressed in costume of a fairy, took her place in one of the tray-like leaves, and, like a Naiad of the waters, presided as the fairy guardian of this beautiful floral queen.*"



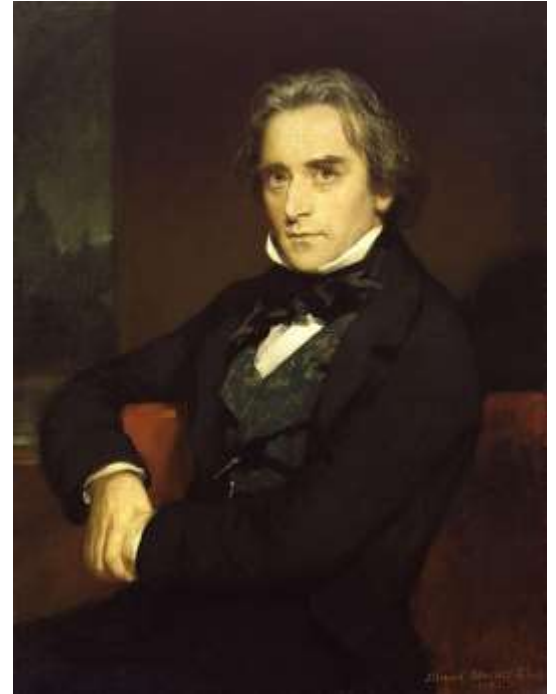


**Douglas W. Jerrold** wrote a poem for the occasion:

*On unbent leaf, in fairy guise  
Reflected in the water,  
Beloved, admired by heart and eyes,  
Stands Annie, Paxton's daughter.*

*Accept a wish, my little maid,  
Begotten at the minute,  
That scenes so bright may never fade,  
You still the fairy in it.*

*That all your life, nor care, nor grief  
May load the winged hours  
With weight to bend a lily's leaf,  
But all around be flowers.*

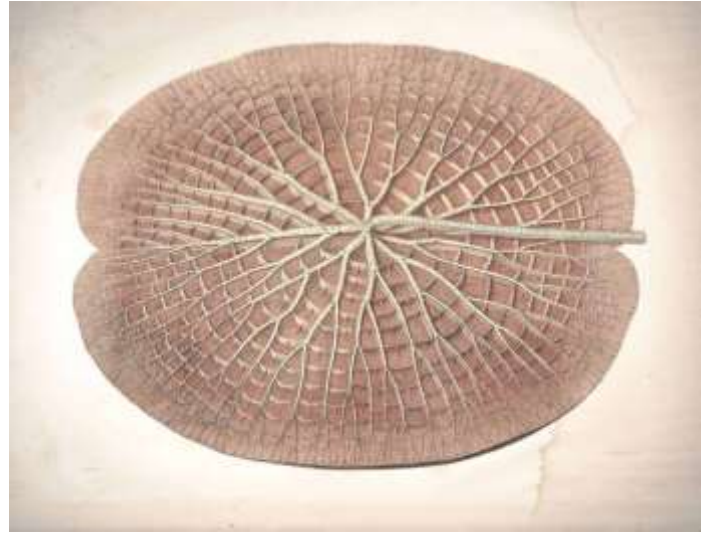


Joseph Paxton had been experimenting with building glass houses, but his interest in *Victoria regia* and the structure of the leaf of *Victoria regia* itself had inspired him to follow new lines in the construction of the building known as the **Lily House** that would house the *Victoria regia*. Paxton's granddaughter, **Violet Rosa Markham** (1935), wrote in *Paxton and the Bachelor Duke*, "*Victoria, amiable throughout her career, apart from her house, actually contributed some structural principles to the Exhibition building. In the paper describing his design, read by Paxton to the Fine Arts*

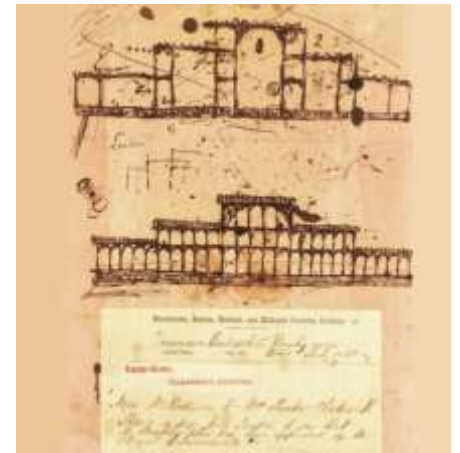




Society on November 13<sup>th</sup>, 1850, he exhibited one of the marvelous leaves five feet in diameter and pointed out that its **underside was a beautiful example of natural engineering**. For it possessed ribs like levers radiating from the centre (where they were nearly two inches deep), with large bottom flanges, and very thin middle ribs with cross girders between each pair to keep the middle ribs from buckling. *'Nature was the engineer,' said Paxton. 'Nature has provided the leaf with longitudinal and transverse girders and supports that I, borrowing from it, have adopted in this building.'*



The Lily House was built entirely out of glass and cast iron. Everything used to build the building had **multiple roles**. The **roof** was a light and heat adjuster; the **supporting columns, rafters** and **sash bars** were also drain pipes. The **floor** was a ventilator and a dust trap. The parts of the Lily house were **prefabricated** and **modular** and could be built **inexpensively** and the same modules could be used to construct variously-designed buildings.



When it was time to design the Great Exhibition of 1851, he used the lessons he had learned from *Victoria regia*, beating out the 245 designs offered by professional architects from all over the world. Paxton's design was selected because it was **inexpensive**, did **not** use bricks and mortar, and could be built and disassembled **quickly**.

Joseph Paxton used the design principles he learned from *Victoria regia* and used to design the Lily House to design the building for the **Great Exhibition of the Works of Industry of all Nations** or the **Great Exhibition of 1851**. Douglas Jerrold, using the pseudonym “Mrs Amelia Mouser (July 13, 1850), described the building that Paxton proposed to build as the “*palace of the very crystal*” and from that time on it was known as the **Crystal Palace**, home of the Great Exhibition of 1851. Using the principles of the economy of nature exhibited in the leaf of *Victoria regia*, Paxton built the Crystal Palace within nine months.







Paxton was knighted and became Sir Joseph Paxton in 1851. Paxton could not only assemble the Crystal Palace easily and quickly but he could also disassemble it easily and quickly so that he could return Hyde Park to the people. He then moved the Crystal Palace from Hyde Park to Sydenham Hill, where it was used for many exhibitions, including a dinosaur exhibit. The Crystal Palace was destroyed in a fire on November 30, 1936.



On September 23, 1851, **T. H. Huxley** wrote to his future wife, Henrietta Anne Heathorn, “*The great Temple of England at present is the Crystal Palace—58,000 people worship these every day. They come up to it as the Jews came to Jerusalem at the time of the Jubilee.*” The Exhibition of 1851 at the Crystal Palace exhibited two specimens of the duck-billed platypus and a specimen of the giant ground sloth prepared by **Richard Owen**. When the Crystal Palace was moved to Sydenham, Prince Albert wanted to include life-sized models of dinosaurs, including the carnivorous Megalosaurus and the herbivorous Iguanodon. Richard Owen, who coined the word **dinosaur** in 1841, was the scientific consultant to the sculptor, Benjamin Waterhouse Hawkins. Over a million people a year came to this exhibit to learn about and enjoy natural history as a part of Victorian culture.





The Crystal Palace may be brought back to life as a 21<sup>st</sup> century cultural attraction by real estate mogul Ni Zhaoxing.

In the 19<sup>th</sup> century, *Victoria regia* came to the United States where its mechanical strength also caused a stir.

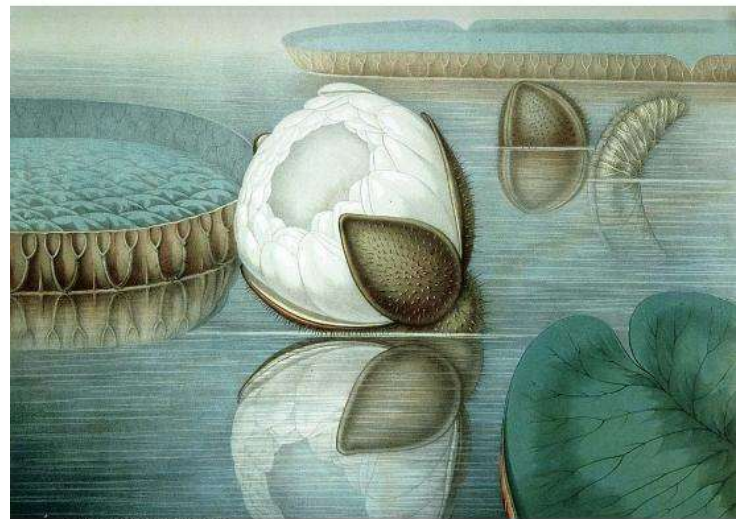
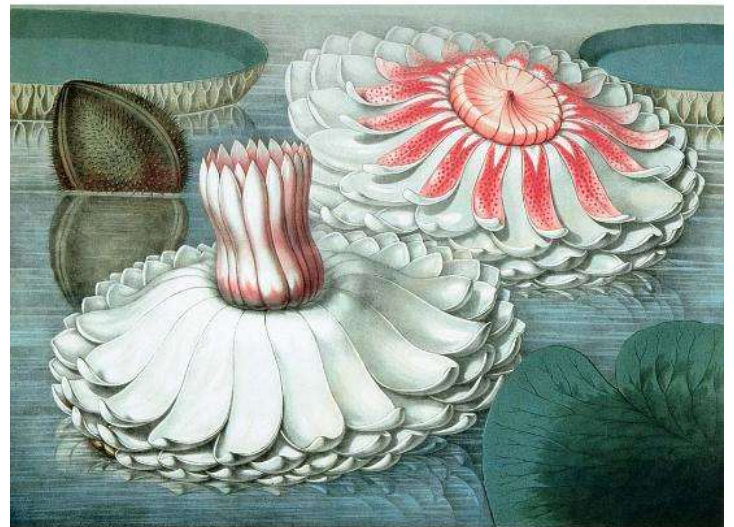


**Karl Niklas** (Cornell), Steven Vogel and Park Nobel study the biomechanics and biophysics, of plants and their leaves.





**John Fisk Allen** wrote and **William Sharp** illustrated *Victoria regia, or The Great Water Lily of America* in 1854. William Sharp drew the images on stones and printed them. Sharp was America's first **chromolithographic printer**, and this book is the earliest example of large scale color printing in the United States. We will see this book in the Rare and Manuscript Collections at Kroch Library.



**Pollination** in *Victoria regia* is as interesting as the leaf. The flower of *Victoria regia* is originally white and opens at night. Only the female parts (pistils)

of the flower are fertile while the **petals are white**. While the flower is white, the core of the flower heats up to about 95 °C. At this temperature, chemicals are volatilized which gives the flower a butterscotch and pineapple scent. This scent attracts pollen-covered **scarab beetles** that will pollinate the flower. At dawn, the petals close around the beetle, and they stay closed for 24 hours while the beetle pollinates the pistil. Consequently, the male parts of the flower (stamens) become fertile. At dusk, the petals turn pink and the flower opens to let out the pollen-covered beetle, which can now fly to a white flower, with fertile female parts.



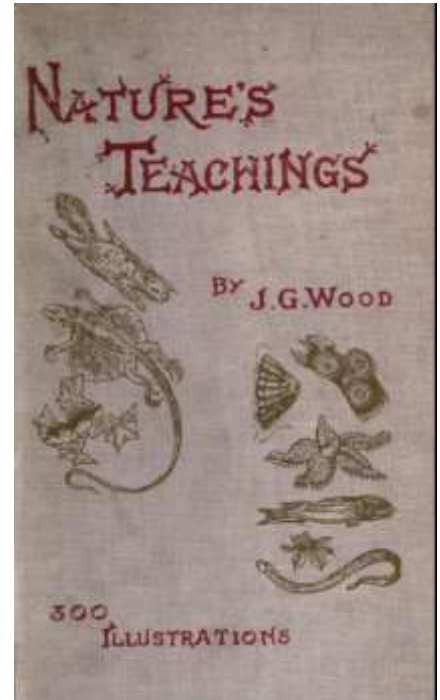
You can watch the lily grow and bloom and be pollinated in time lapse  
[http://www.youtube.com/watch?v=igkjcuw\\_n\\_U](http://www.youtube.com/watch?v=igkjcuw_n_U)

**Mann Library Special Collections**  
has *Victoria regia, or Illustrations of the Royal Water-Lily, in a Series of Figures Chiefly Made from Specimens Flowering at Syon and at Kew* by Sir William Jackson Hooker and Walter Hood Fitch printed by Bradbury & Evans for Reeve & Benham in 1851. (Call Number: QK495.N97 F5 Oversize)





In *Nature's Teachings*, the Reverend J. G. Wood (1858, 1907) wrote, "*The capabilities of the Crystal Palace had lain latent for centuries, but the generalising eye of genius was needed to detect it. A thousand men might have seen the Victoria Regia leaf, and not thought very much of it; but the right man came at the right time, the most wonderful building in the world sprang up like the creation of a fairy dream, and the obscure gardener became Sir Joseph Paxton. I have no doubt that thousands of similar revelations are at present hidden in Nature, awaiting the eye of their revealer.*" You can learn a lot from botany and looking at a leaf, the organ that specializes in photosynthesis.



## ***Botany***

by Berton Braley (1929)

*There should be no monotony  
In studying your botany;  
It helps to train  
And spur the brain--  
Unless you haven't got any.*

*It teaches you, does Botany,  
To know the plants and spotany,  
And learn just why  
They live or die--  
In case you plant or potany.*



*You learn, from reading Botany,  
Of wooly plants and cottony  
That grow on earth,  
And what they're worth,  
And why some spots have notany.*

*You sketch the plants in Botany,  
You learn to chart and plotany  
Like corn or oats--  
You jot down notes,  
If you know how to jotany.*

*Your time, if you'll allotany,  
Will teach you how and what any  
Old plant or tree  
Can do or be--  
And that's the use of Botany!*

